ACTIVE FILTERS

Lecture 9

OVERVIEW

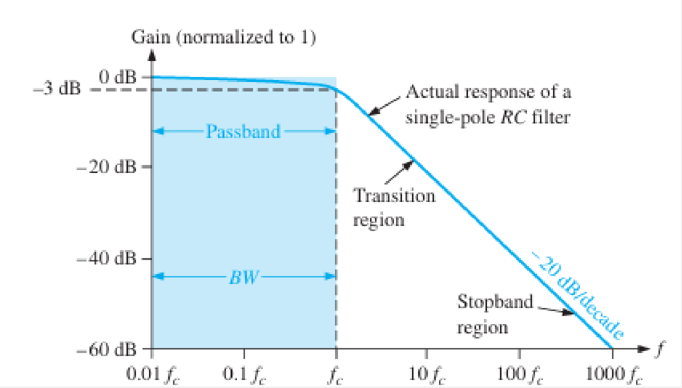
- Basic Filter Reponses
- Filter Response Characteristics
- Active Low-Pass Filters
- Active High-Pass Filters
- Active Band-Pass Filters
- Active Band-Stop Filters

BASIC FILTER RESPONSES

A **filter** is a circuit that passes certain frequencies and attenuates or rejects all other frequencies. Filters are usually categorized by the manner in which the output voltage varies with the frequency of the input voltage. The categories of active filters:

- Low-pass
- High pass
- Band-pass
- Band-stop

The **passband** of a filter is the range of frequencies that are allowed to pass through the filter with minimum attenuation (usually defined as less than $-3dB$ of attenuation). The **critical frequency**, (also called the *cutoff frequency*) defines the end of the passband and is normally specified at the point where the response drops $-3dB$ (70.7%) from the passband response. Following the *passband* is a region called the *transition* region that leads into a region called the *stopband*. There is no precise point between the *transition region* and the *stopband*.



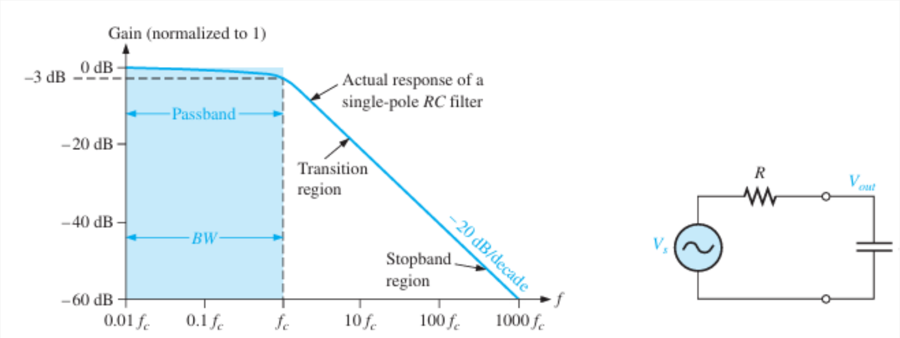
LOW-PASS FILTER RESPONSE

- Passes frequencies from DC (0 Hz) to f_c and significantly attenuates all other frequencies. The response drops to zero at frequencies beyond the pass band. The bandwidth of an ideal low-pass filter is equal to f_c.

$$BW = f_c$$

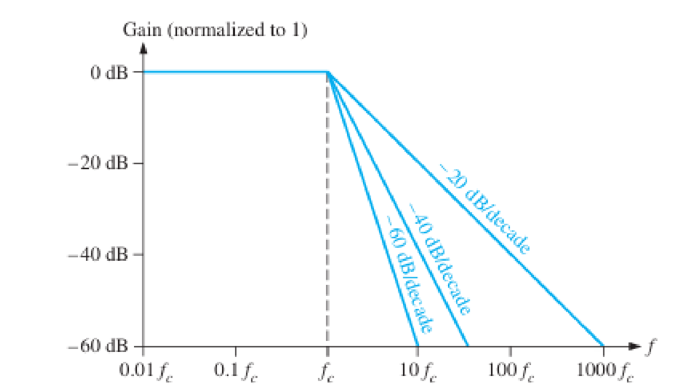
- Actual filter responses depend on the number of poles, a term used with filters to describe the number of RC circuits contained in the filter.
- The most basic low-pass filter is a simple RC circuit consisting of just one resistor and one capacitor; the output is taken across the capacitor. This basic RC filter has a single pole, and it rolls off at $-20db/decade$ beyond the critical frequency.
- The $-20dB/decade$ **roll-off** rate for the gain of a basic RC filter means that at a frequency of $10\ f_c$, the output will be $-20dB$ (10%) of the input.
- The gain drops off slowly until the frequency is at the critical frequency; after this, the gain drops rapidly.
- The critical frequency of a low-pass RC filter occurs when $X_C = R$, where

$$f_c = \frac{1}{2\pi RC}$$



(a) Comparison of an ideal low-pass filter response (blue area) with actual response. Although not shown on log scale, response extends down to $f_c = 0$.

(b) Basic low-pass circuit

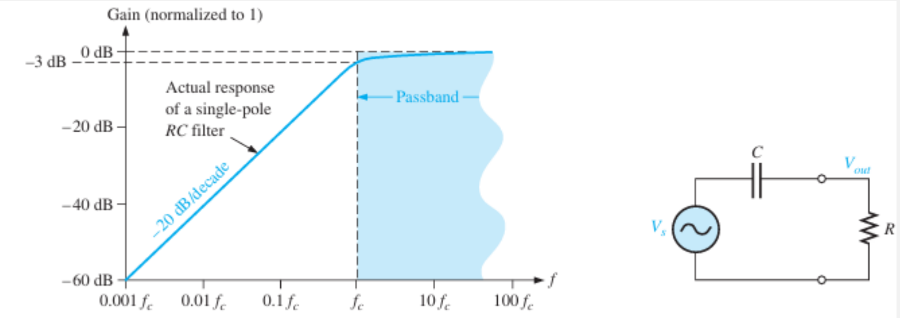


(c) Idealized low-pass filter responses

HIGH-PASS FILTER RESPONSE

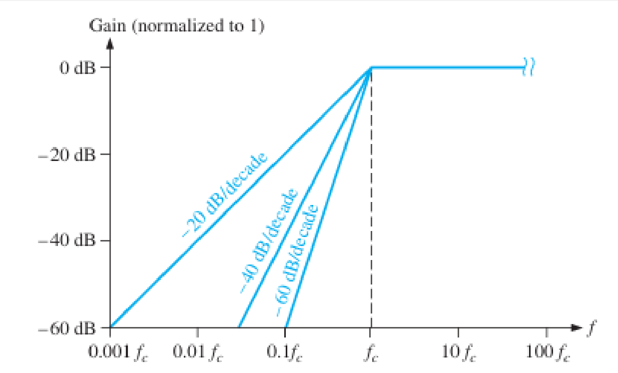
- Significantly attenuates or rejects all frequencies below and passes all frequencies above $\boldsymbol{f_c}$.
- The critical frequency is, again, the frequency at which the output is 70.7% of the input (or $-\,3dB$)
- The ideal response, indicated by the blue-shaded area, has an instantaneous drop at which, of course, is not achievable.
- Ideally, the passband of a high-pass filter is all frequencies above the *critical frequency*. The high-frequency response of practical circuits is limited by the op-amp or other components that make up the filter.
- A simple RC circuit consisting of a single resistor and capacitor can be configured as a high-pass filter by taking the output across the resistor as shown in Figure below. The critical frequency for the basic high pass filter occurs when $X_C \;=\; R$, where

$$f_c = \frac{1}{2\pi RC}$$



(a) Comparison of an ideal high-pass filter response (blue area) with actual response

(b) Basic high-pass circuit



(c) Idealized high-pass filter responses

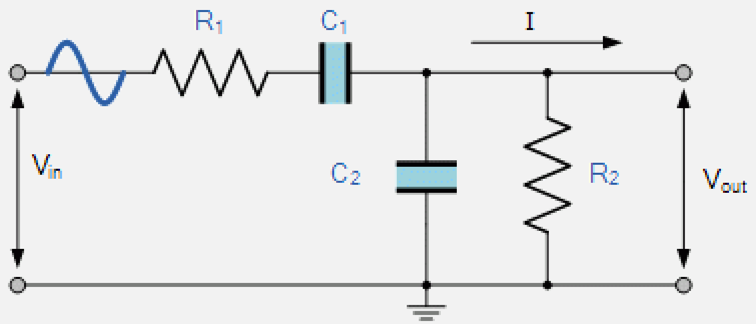
BAND-PASS FILTER RESPONSE

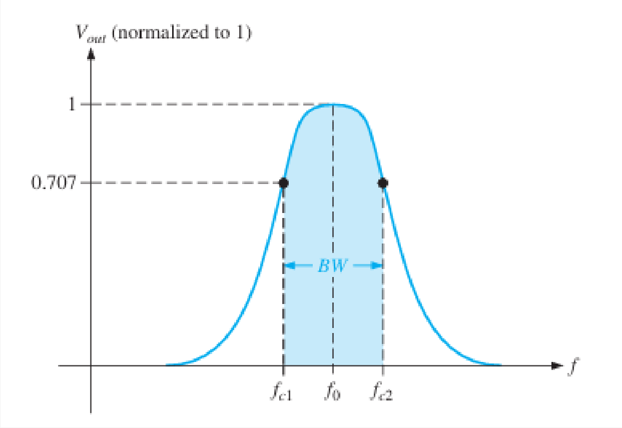
- Passes all signals lying within a band between a lower-frequency limit and an upper-frequency limit and essentially rejects all other frequencies that are outside this specified band.
- The bandwidth (BW) is defined as the difference between the upper critical frequency (f_{c2}) the lower critical frequency (f_{c1}).

$$BW = f_{c2} - f_{c1}$$

- The critical frequencies are the points at which the response curve is 70.7% of its maximum. The frequency about which the passband is centered is called the *center frequency*, f_0, defined as the geometric mean of the critical frequencies.

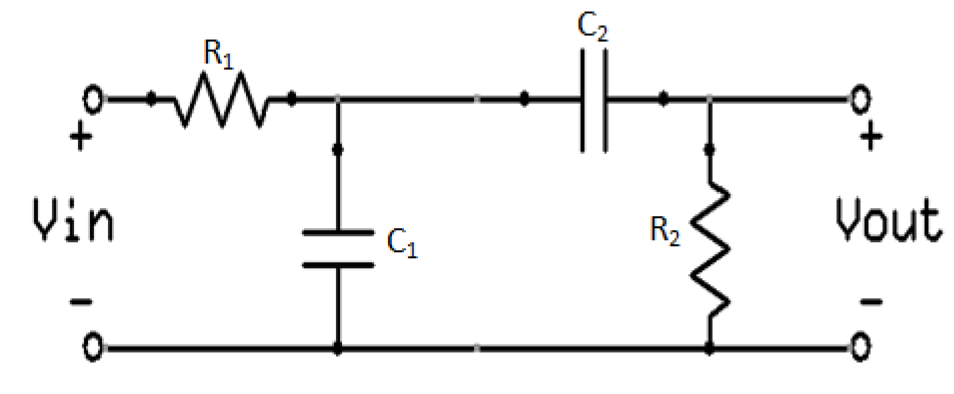
$$f_0 = \sqrt{f_{c1} f_{c2}}$$

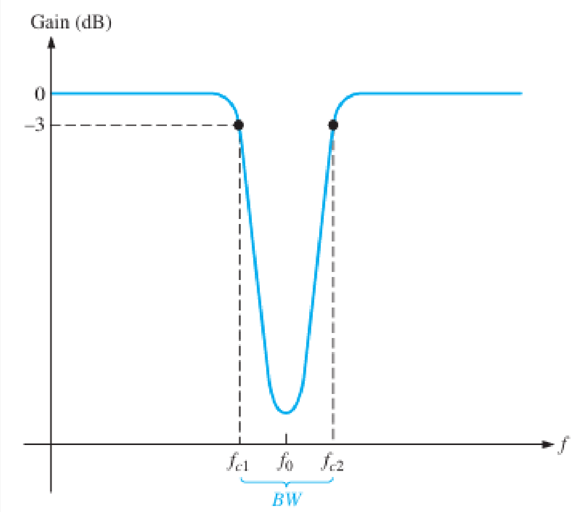




BAND-STOP FILTER RESPONSE

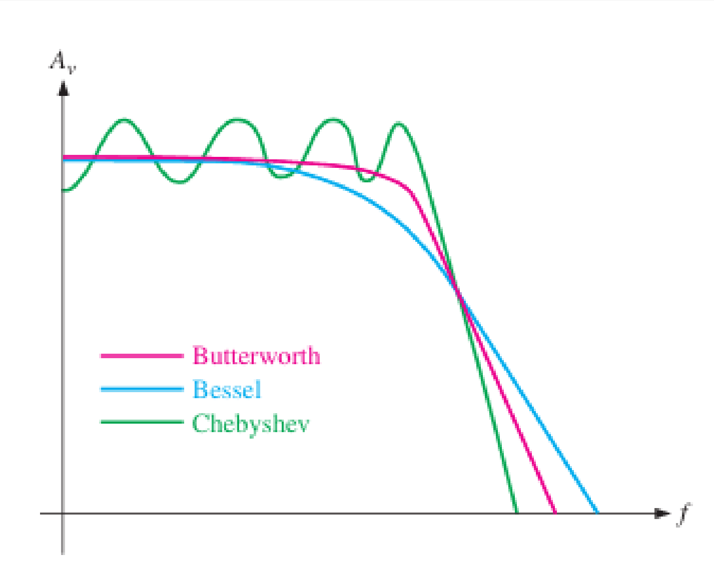
- Also known as *notch*, *band-reject*, or *band-elimination* filter.
- The operation is opposite to that of the band pass filter because frequencies within a certain bandwidth are rejected, and frequencies outside the bandwidth are passed.
- The bandwidth is the band of frequencies between the 3 *dB* points, just as in the case of the band-pass filter response.





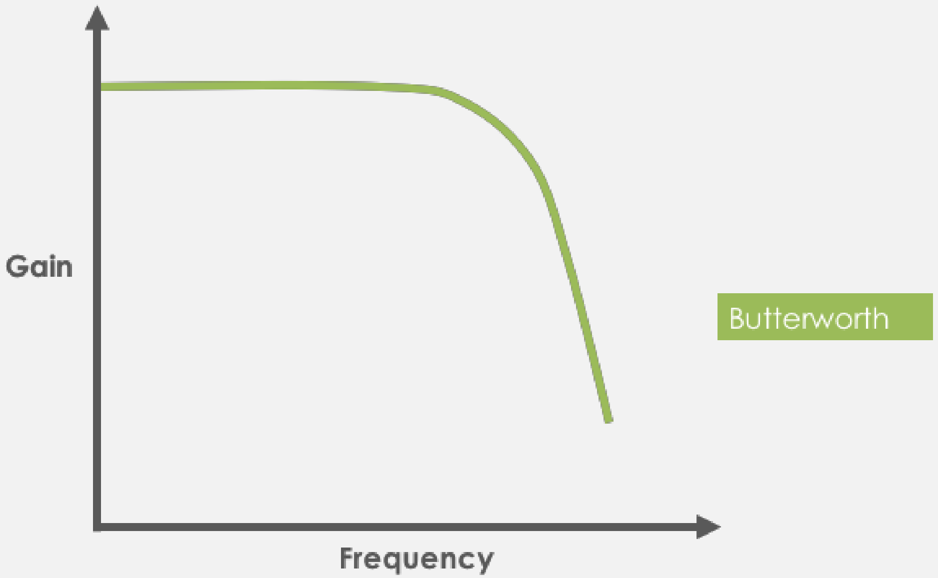
FILTER RESPONSE CHARACTERISTICS

- Each type of filter response (low-pass, high-pass, band-pass, or band-stop) can be tailored by circuit component values to have either a *Butterworth*, *Chebyshev*, or *Bessel* characteristic. Each of these characteristics is identified by the shape of the response curve, and each has an advantage in certain applications.
- *Butterworth*, *Chebyshev*, or *Bessel* response characteristics can be realized with most active filter circuit configurations by proper selection of certain component values.



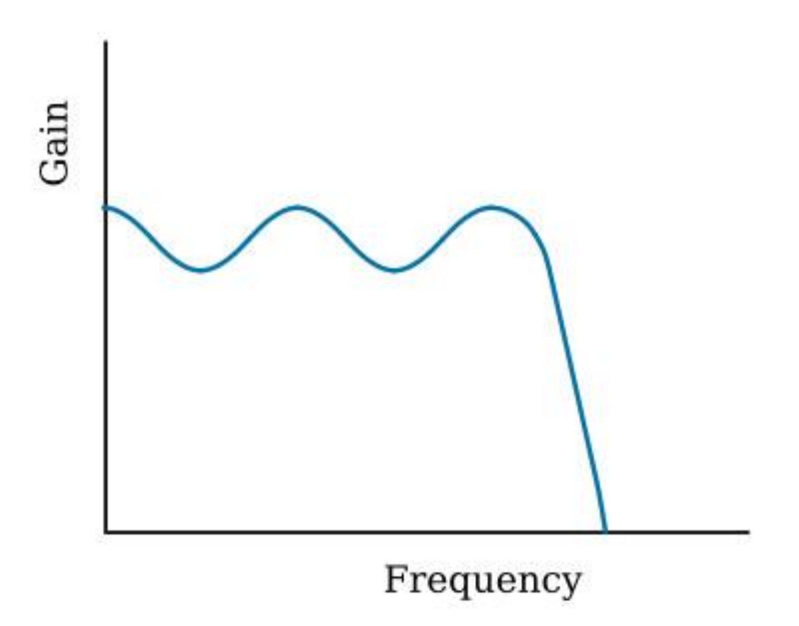
BUTTERWORTH CHARACTERISTICS

- The ***Butterworth*** characteristic provides a very flat amplitude response in the passband and a roll-off rate of -20 dB/decade/pole. The phase response is not linear, however, and the phase shift (thus, time delay) of signals passing through the filter varies nonlinearly with frequency. Therefore, a pulse applied to a filter with a Butterworth response will cause overshoots on the output because each frequency component of the pulse's rising and falling edges experiences a different time delay. Filters with the Butterworth response are normally used when all frequencies in the passband must have the same gain. The Butterworth response is often referred to as a maximally flat response.



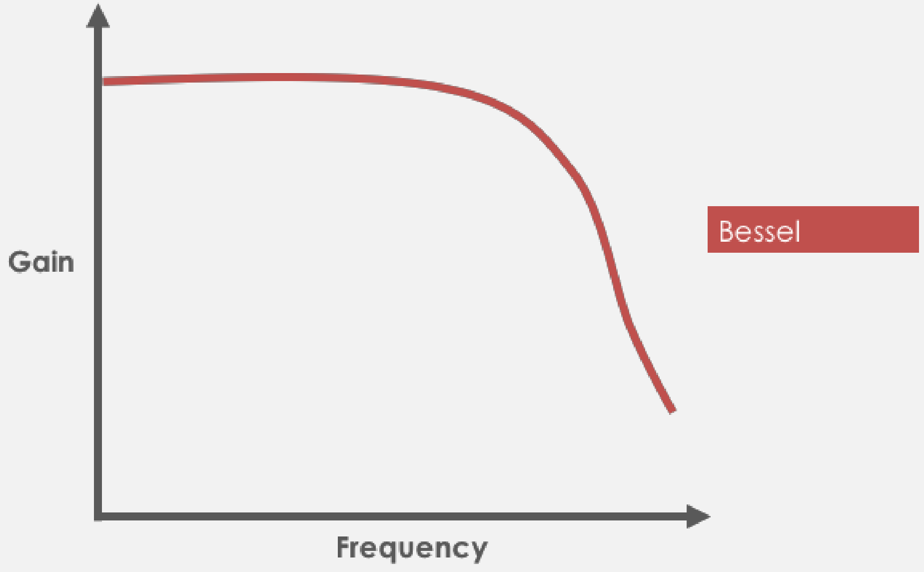
CHEBYSHEV CHARACTERISTICS

- Filters with the ***Chebyshev*** response characteristic are useful when a rapid roll-off is required because it provides a roll-off rate greater than -20 dB/decade/pole. This is a greater rate than that of the Butterworth, so filters can be implemented with the Chebyshev response with fewer poles and less complex circuitry for a given roll-off rate. This type of filter response is characterized by overshoot or ripples in the passband (depending on the number of poles) and an even less linear phase response than the Butterworth.



BESSEL CHARACTERISTICS

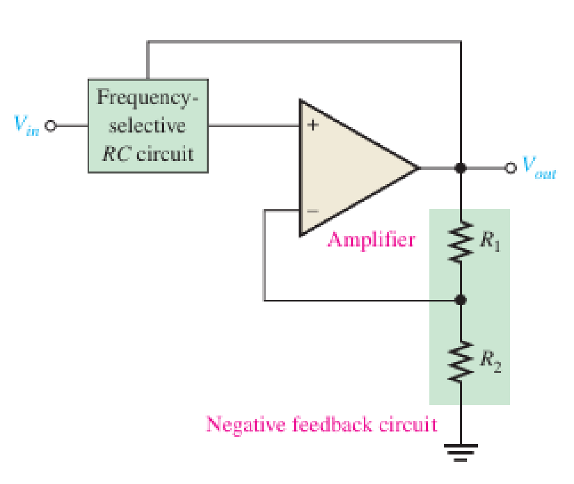
- The ***Bessel*** response exhibits a linear phase characteristic, meaning that the phase shift increases linearly with frequency. The result is almost no overshoot on the output with a pulse input. For this reason, filters with the Bessel response are used for filtering pulse waveforms without distorting the shape of the waveform.



DAMPING FACTOR

- An active filter can be designed to have either a Butterworth, Chebyshev, or Bessel response characteristic regardless of whether it is a low-pass, high-pass, band-pass, or band-stop type. The ***damping factor*** (**DF**) of an active filter circuit determines which response characteristic the filter exhibits. The value of the damping factor required to produce a desired response characteristic depends on the **order** (*number of poles*) of the filter.
- A generalized active filter includes an amplifier, a negative feedback circuit, and a filter section. The amplifier and feedback are connected in a noninverting configuration.
- The damping factor is determined by the negative feedback circuit and is defined by the following equation:

$$DF = 2 - \frac{R_1}{R_2}$$



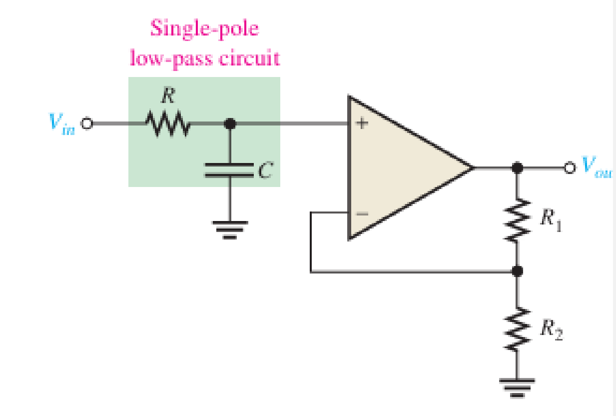
- Any attempted increase or decrease in the output voltage is offset by the opposing effect of the negative feedback. This tends to make the response curve flat in the passband of the filter if the value for the damping factor is precisely set.

CRITICAL FREQUENCY AND ROLL-OFF RATE

- The critical frequency is determined by the values of the resistors and capacitors in the frequency-selective RC circuit. For a single-pole (first-order) filter, the critical frequency is

$$f_c = \frac{1}{2\pi RC}$$

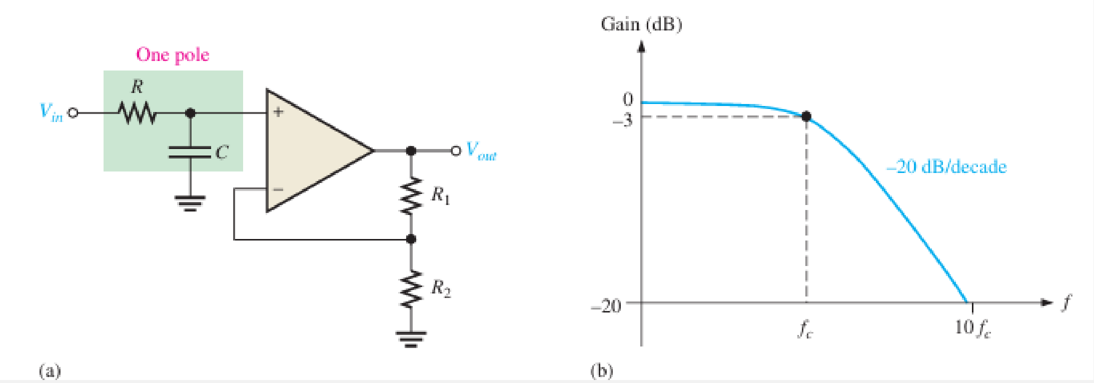
- The number of poles determines the ***roll-off rate*** of the filter. A Butterworth response produces $-20dB/decade/pole$. So, a first-order (one-pole) filter has a roll-off of $-20\ dB/decade$; a second-order (two-pole) filter has a roll-off rate of $-40\ dB/decade$, a third-order (three-pole) filter has a roll-off rate of -60 $dB/decade$; so on.



ACTIVE LOW-PASS FILTER

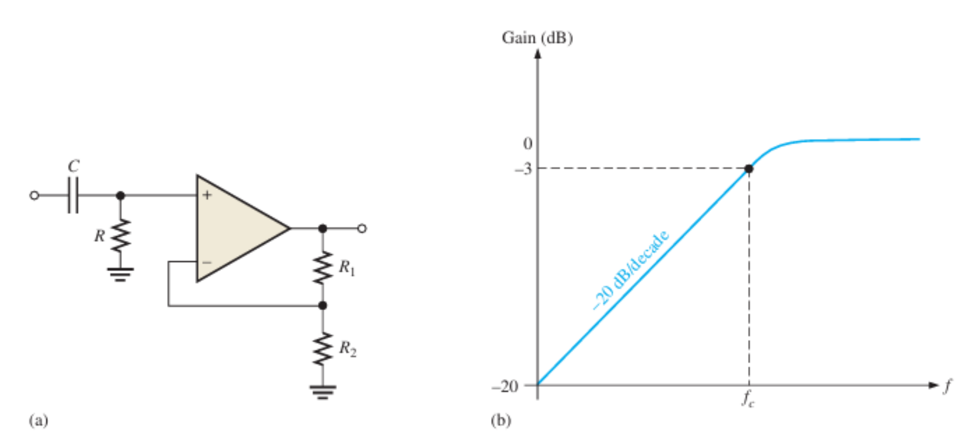
- Filters that include one or more op-amps in the design are called ***active*** filters.
- Filters that use op-amps as the active element provide several advantages over passive filters (R, L, and C elements only). The op-amp provides gain, so the signal is not attenuated as it passes through the filter. The high input impedance of the op-amp prevents excessive loading of the driving source, and the low output impedance of the op-amp prevents the filter from being affected by the load that it is driving. Active filters are also easy to adjust over a wide frequency range without altering the desired response.
- Figure below shows an active filter with a single low-pass RC frequency-selective circuit that provides a roll-off of $-20dB/decade$ above the critical frequency, as indicated by the response curve. The critical frequency of the single-pole filter is $f_c = 1/(2\pi RC)$.
- The op-amp in this filter is connected as a noninverting amplifier with the closed-loop voltage gain in the passband set by the values of R_1 and R_2:

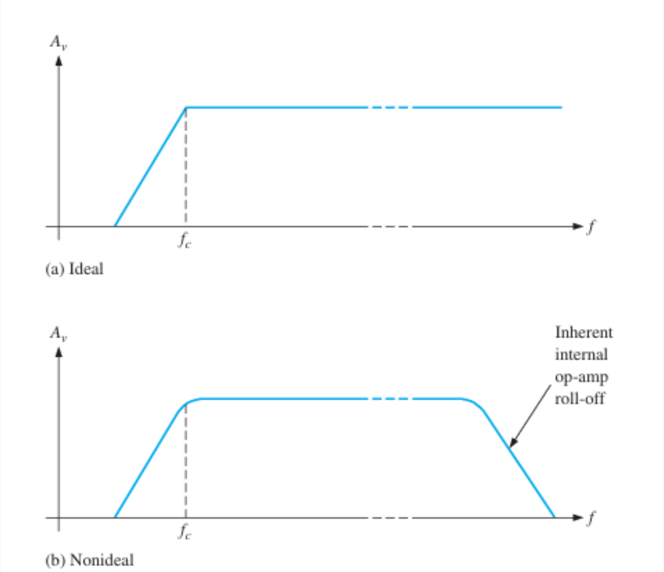
$$A_{cl(NI)} = \frac{R_1}{R_2} + 1$$



ACTIVE HIGH-PASS FILTER

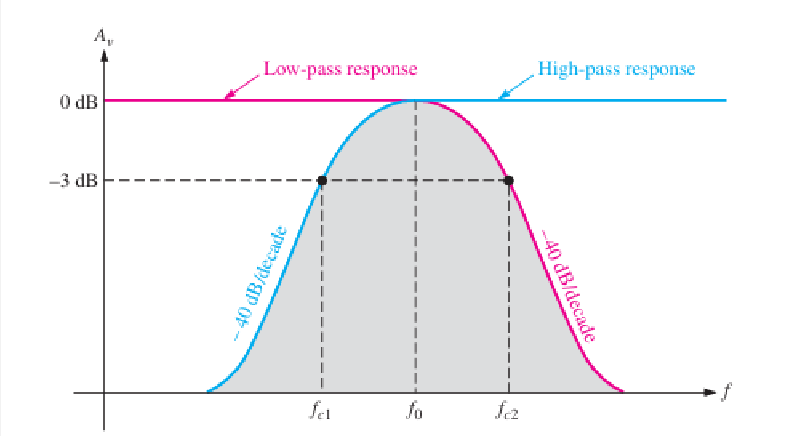
- The input circuit is a single high-pass RC circuit. The negative feedback circuit is the same as for the low-pass filters previously discussed.
- Ideally, a high-pass filter passes all frequencies above f_c without limit, although in practice, this is not the case.
- All op-amps inherently have internal RC circuits that limit the amplifier's response at high frequencies.
- Therefore, there is an upper-frequency limit on the high-pass filter's response which, in effect, makes it a band-pass filter with a very wide bandwidth.





ACTIVE BAND-PASS FILTER

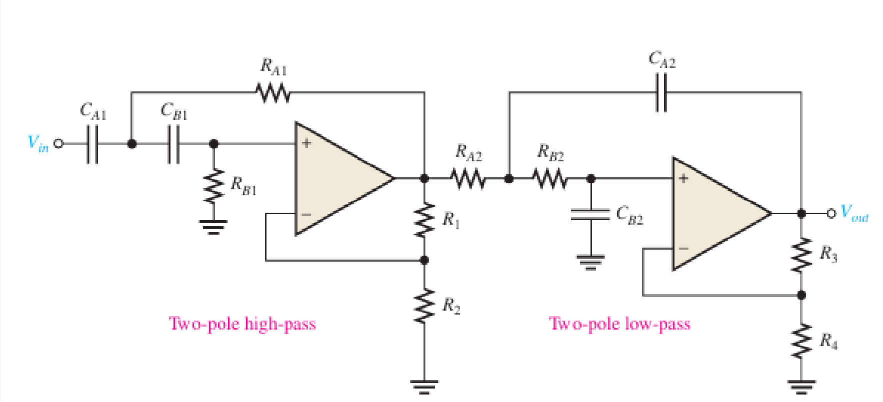
- Band-pass filters pass all frequencies bounded by a lower-frequency limit and an upper-frequency limit and reject all others lying outside this specified band. A band-pass response can be thought of as the overlapping of a low-frequency response curve and a high-frequency response curve.
- One way to implement a band-pass filter is a cascaded arrangement of a high-pass filter and a low-pass filter, as long as the critical frequencies are sufficiently separated.
- The critical frequency of each filter is chosen so that the response curves overlap sufficiently, as indicated. The critical frequency of the high-pass filter must be sufficiently lower than that of the low-pass stage. This filter is generally limited to wide bandwidth applications.
- The lower frequency of the passband is the critical frequency of the high-pass filter. The upper frequency is the critical frequency of the low-pass filter. Ideally, as discussed earlier, the center frequency of the passband is the geometric mean of f_{c1} and f_{c2}



$$f_{c1} = \frac{1}{2\pi\sqrt{R_{A1}R_{B1}C_{A1}C_{B1}}}$$

$$f_{c2} = \frac{1}{2\pi\sqrt{R_{A2}R_{B2}C_{A2}C_{B2}}}$$

$$f_0 = \sqrt{f_{c1}f_{c2}}$$



ACTIVE BAND-STOP FILTER

- Band-stop filters reject a specified band of frequencies and pass all others. The response is opposite to that of a band-pass filter.
- Band-stop filters are sometimes referred to as *notch filters*.
- Figure below shows a multiple-feedback band-stop filter.